REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-01-
0601

...38

1. REPORT DATE *(DD-MM-YYYY)* 10/25/2001	2. REPORT TYPE Final	3. DATES COVERED *(From - To)* 5/15/00-5/14/01
4. TITLE AND SUBTITLE Request for Critical Components for MBE and MOVCD to Pursue High Purity GaN at Virginia Microelectronics Center (VMC)		5a. CONTRACT NUMBER 5b. GRANT NUMBER F49620-00-1-0308 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Hadis Morkoç		5d. PROJECT NUMBER 5e. TASK NUMBER 3484/US 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Virginia Commonwealth University, School of Engineering PO Box 980568 Richmond, VA 23298-0568		8. PERFORMING ORGANIZATION REPORT NUMBER 1
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NE Dr. Gerald L. Witt, Program Manager 801 N. Randolph Street Room 732 Arlington, VA 22203-1977		20011203 188
12. DISTRIBUTION / AVAILABILITY STATEMENT		
13. SUPPLEMENTARY NOTES		

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14. ABSTRACT

A Lake Shore Model 7504 variable temperature Hall measurement apparatus was procured and installed in August 2000. The system has been in use for nearly a year now and has already become a indispensible component of our research effort. Since the funds provided were not sufficient for a brand new one, we opted to purchase a laboratory model with warranty identical to that for a standard system. The apparatus is able to automatically collect Hall data in a temperature range of 10-300K and under magnetic fields up to about 8 KGauss. The **IDEAS Hall Application Software** is very user friendly and optimum for doing the necessary initial trial and error runs to obtain reliable data. The lack of such a software in home made systems in the past led to erroneous data which often times made into publications as well.

The apparatus included instrument rack, 4"electromagnet, power supply and mounting hardware, and cabling; Keithley Models 7065 Hall effect card 7001 Switch system, 220 current source, 182 voltmeter, 480 picoammeter ; Lake Shore Models Temperature controller, 450 Gaussmeter and 75013 RT/77K Sample Holder Module. New Computer and 17" monitor with IEEE-488 card IDEAS Hall Application Software. In house 75014 Closed Cycle Refrigerator Sample module and APD Compressor and came with a full 12 month manufacturer warranty. The system price also included a two-day installation and training charge. The total cost of acquisition was $95,000.00

15. SUBJECT TERMS
semiconductor materials, magnetoresistors, GMR films, high temperature superconductors

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Herbert B. Chermside, CRA
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	Unlimited	27	19b. TELEPHONE NUMBER *(include area code)* 804-828-6772

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

DURIP 00 Final Report for

Request for Critical Components for MBE and MOVCD to Pursue High Purity GaN at Virginia Microelectronics Center (VMC)

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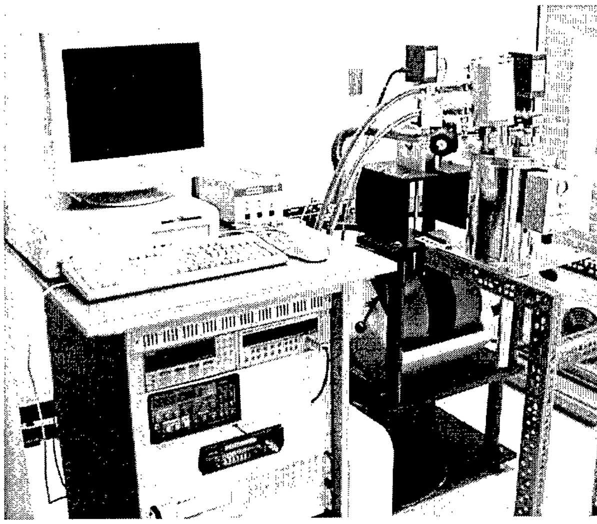
Summary

A Lake Shore Model 7504 variable temperature Hall measurement apparatus was procured and installed in August 2000. The system has been in use for nearly a year now and has already become a indispensible component of our research effort. Since the funds provided were not sufficient for a brand new one, we opted to purchase a laboratory model with warranty identical to that for a standard system. The apparatus is able to automatically collect Hall data in a temperature range of 10-300K and under magnetic fields up to about 8 KGauss. The **IDEAS Hall Application Software** is very user friendly and optimum for doing the necessary initial trial and error runs to obtain reliable data. The lack of such a software in home made systems in the past led to erroneous data which often times made into publications as well.

The apparatus included instrument rack, 4"electromagnet, power supply and mounting hardware, and cabling; Keithley Models 7065 Hall effect card 7001 Switch system, 220 current source, 182 voltmeter, 480 picoammeter ; Lake Shore Models Temperature controller, 450 Gaussmeter and 75013 RT/77K Sample Holder Module. New Computer and 17" monitor with IEEE-488 card IDEAS Hall Application Software. In house 75014 Closed Cycle Refrigerator Sample module and APD Compressor and came with a full 12 month manufacturer warranty. The system price also included a two-day installation and training charge. The total cost of acquisition was $95,000.00

The figure shows a photograph of the Hall setup as it stands in our laboratory. The same can also be found in our web site. The text attached is the description that can accompanies the photo in the web site.



Lake Shore Model 7504 Hall effect apparatus is used for temperature and magnetic field dependent measurements in the temperature range of 7-300 K and in magnetic field strengths up to 7 KGauss.

Lake Shore's 7500 Series Hall Effect/Electronic Transport Measurement System is an advanced integrated hardware and software system designed to characterize and analyze the electronic transport properties of materials. Designed for easy and precise operation, Lake Shore's 7500 Series Systems allow the user to control both temperature and magnetic induction (field) while measuring a sample material. IDEAS Hall is Windows 95 menu driven, enhanced color-graphic software for system operation, data acquisition and analysis. Easy to operate, the IDEAS Hall software is designed to control system instrumentation throughout the course of an experiment and determine sample resistance, resistivity, Hall coefficient, Hall mobility, carrier concentration, or current-voltage characteristics. System software includes individual instrument drivers for complete front panel operation and control of the magnet power supply and instrument console. Real-time feedback of processed measurement data can be displayed in graphical and tabular format. IDEAS software helps record data automatically for 4-contact van der Pauw samples and 6-contact Hall bar samples and stores data to the hard drive to be used for further processing, analysis, and display. It also allows the user to write custom programs in Visual BASIC or other languages to access the IDEAS Hall software using the Object Linking and Embedding interface (OLE).

Specifics of Lake Shore Model 7504 Hall Effect Measurement System

Hall effect and electronic transport measurements are invaluable in characterizing the properties of a wide variety of semiconductor materials such as Si, Ge, GaAs, GaN, AlGaAs, CdTe, HgCdTe, as well as magnetoresistors, GMR films, and high temperature superconductors. Additional information can be gained by taking transport Hall effect measurements as a function of magnetic induction (field) or temperature. Transport measurements of Hall effect and magnetoresistance are ideally suited for materials research, product development and quality control.

Lake Shore's 7500 Series Hall Effect/Electronic Transport Measurement System is an advanced integrated hardware and software system designed to characterize and analyze the electronic transport properties of materials. Designed for easy and precise operation, Lake Shore's 7500 Series Systems allow the user to control both temperature and magnetic induction (field) while measuring a sample material.

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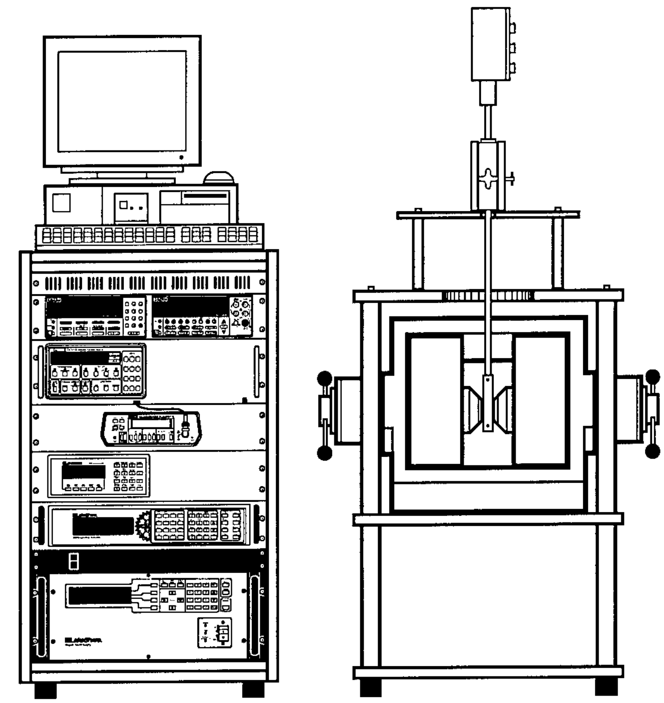

Materials

Electronic conductors, including semiconductors, metals and superconductors. Thin films, heterostructures, bulk materials (single crystal or polycrystalline). Single or multiple carrier.

Applications

Make measurements for mobility spectrum analysis to evaluate multilayered materials and measure the individual properties of multiple carriers.

Verify doping effectiveness by measuring active carrier concentrations.

Check base contamination levels to determine impurity levels in semiconductor growth systems such as chemical vapor deposition (CVD) and molecular beam epitaxy (MBE).

Lake Shore Hall Measurement Systems . . .

- Measure Hall voltage, resistance, magnetoresistance, and current-voltage characteristics with one system.
- Calculate resistivity, Hall coefficient, and carrier concentration and mobility.
- Vary temperature (with options) and magnetic field to determine the effects on materials.
- Reduce the amount of time spent making measurements by using the fully integrated, automated computer data collection system which makes measurements and calculates the results.
- Controls, monitors and changes instrument settings throughout the experiment using IDEAS Hall software. Software includes individual instrument drivers for complete on-screen, virtual front panel control and operation of all instrumentation.
- Produce more accurate, repeatable measurements using a magnetic field that is actively controlled and stabilized by IDEAS Hall software.
- Make measurements for mobility spectrum analysis using a variable field magnet. Mobility spectrum analysis allows you to evaluate multilayered materials and measure individual properties of multiple carriers.
- Measure samples with resistances ranging from 1 Ω to 1.5 x 10^{11} Ω with less than 2% measurement uncertainty with the standard 7500 Series instrumentation.
- Display real-time feedback of processed measurement data in either graphical or tabular format as the experiment is taking place.
- Allow the user to write custom programs in Visual BASIC or other languages to access the IDEAS Hall software using the Object Linking and Embedding interface (OLE).
- Produce excellent field stability using water cooled magnet coils, feedback control, high quality sensors, and advanced electronics.
- Quickly make measurements with the standard Model 75013 Sample Card Sample Module using samples mounted on plug-in sample cards.
- Measure materials at temperatures as low as 15 K using the optional Model 75014 Closed Cycle Refrigerator Sample Module.
- Customize the system with additional options, including a Hall bar configuration, high sensitivity, and fully automated switching option.

System Specifications

General

Sample interface	Model 75013 RT/77 K Sample Card Sample Module is included as standard equipment. The two-temperature environment uses liquid nitrogen to reach 77 K. The sample probe and the attachment base are provided. Plug-in samples facilitate sample exchange and storage.
Sample size	12 mm square maximum on a 25 x 75 mm plug-in card (50 provided) or 60 mm square maximum on an 82 x 93 mm plug-in card (10 provided)
Sample geometry	Hall bar or van der Pauw
Number of contacts	4 or 6
Shunt resistance	>10 teraohms (10^{13} Ω)
Temperature	Room temperature or 77 K (liquid nitrogen required for 77 K)
Voltage range	100 V, 100 mA (depends on configuration)
Resistance range	0.1 mΩ to 200 GΩ (depends on configuration)

Equipment

Keithley Instruments Model 7065 Hall effect card in a Model 7001 Switch System Mainframe
Keithley Instruments Model 220 Current Source
Keithley Instruments Model 2000 Digital Multimeter
Keithley Instruments Model 485/4853 Autoranging Digital Picoammater with IEEE-488 interface

Lake Shore Model 450 Gaussmeter

Resolution	±1 part out of 300,000
Ranges	Seven ranges from 300.000 mG to 300.000 kG (30 μT to 30 T) full scale
Precision	Up to 0.007% of full scale for 300 G and above ranges

Hall Probe ±30 kG (±3 T)

Model 75013 Sample Holder Module

IDEAS™ Hall Software

Model EM4-HV Electromagnet (variable gap)

Pole diameter	10.2 cm (4")	
Pole face diameter	10.2 cm (4")	
	Min. (room temperature) (dewar/oven)	Max.
Air gap	2.5 cm (1")	5.1 cm (2")
Maximum magnetic field	1.04 T (10.4 kG)	0.65 T (6.5 kG)
Magnetic field homogeneity		
over central 1 cm³	±0.05%	±0.1%
±1% centered cylindrical volume	6.4 cm dia. x 2.5 cm	3.8 cm dia. x 5.0 cm
Cooling water requirements	Tap water or closed cooling system (optional chiller available)	
Inlet temperature	32 °C (90 °F) maximum	
Supply pressure	240 to 700 kPa (35 to 110 psig) at rated flow	
Flow rate	3.8 liters per minute (1 gallon per minute)	
Water chiller cooling capacity	1.8 kW (6142 BTU/hr)	

Model 647 Four-Quadrant Magnet Power Supply

Maximum output	±32 V/±72 A (2 kW maximum)
AC line input	200/208/220/ 240 VAC, 50 or 60 Hz

Computer

Pentium computer with hard drive, 3.5" 1.44 MB floppy drive, SVGA color monitor, provided with Windows® 95 and National Instruments IEEE-488 interface. Minimum requirement is 486-DX with 16 megabytes of RAM.

Options

QMSA Software Option (750QMSA)

Lake Shore's Qauntitative Mobility Spectrum Analysis (QMSA) package represents the most advanced multi-carrier analysis capability available. The package analyzes data recorded using the Lake Shore HMS's and automatically segregates mobility spectrum for each carrier species that comprises a multi-layer or multi-carrier material, for example heterostructures, quantum wells, multiply doped materials, etc.

Sample Card Sample Module (75013)

The 75013 room temperature and 77K sample card module includes plug-in sample cards for easy sample exchange. The cards provide for Hall bar or van der Pauw configurations, and accommodate samples to 12 mm x 12 mm.

High Sensitivity Option (750HS)

A sensitive digital nanovoltmeter (Keithley Model 182 Digital Voltmeter) is incorporated into the system to provide much greater voltage sensitivity and accuracy. This option is useful for measuring heavily doped, low mobility, and low resistance samples.

Fully Automated Switching Option (750SWT)

A Keithley 7152 Low Current Switch Card is added, along with the necessary cabling and software to allow automated switching between sample types. The current meter (2 mA maximum) is also switched in and out automatically to allow operation from 500 fA to 100 mA without recabling.

Sample geometry	Hall bar or van der Pauw
Number of contacts	4 or 6
Shunt resistance	>1 teraohms ($10^{12}\ \Omega$)

Temperature Controller Option (750TC)

The 750TC option adds a Lake Shore Model 340 Cryogenic Temperature Controller to the basic system. This allows the user to measure and record the temperature of the sample holder module. When used in conjunction with a heater or oven, the system can control the sample temperature.

Closed Cycle Refrigerator Sample Holder Module Option (75014)

Provides a variable temperature environment with helium exchange gas cooled by a closed cycle refrigerator. No liquid cryogens are required. The sample probe and rotation stage are provided. The sample is surrounded by helium gas at a pressure slightly above atmospheric, so samples can be changed without breaking vacuum or warming up the cryopump. The 750TC Temperature Controller Option must be ordered separately. Pump out of the vacuum jacket to 100 Pa (0.1 torr) is required before cooldown. Operation for more than one week continuously or at temperatures greater than room temperature requires a dedicated diffusion pump or turbomolucular pump.

Cryostat	APD Omniplex with 204SL closed cycle refrigerator and compressor, water cooled (3 L/min)
Temperature range	15 K to 350 K
Sample geometry	12 mm square maximum; van der Pauw or Hall bar geometry
Contacts	6 solder posts provided; 6 additional, unguarded feed through pins available on connector

Publications resulting directly from the use of the AFM

1. F. Yun, M. A. Reshchikov, K. M. Jones, P. Visconti, H. Morkoç, S. S. Park and K. Y. Lee, "Electrical, Structural, and Optical Characterization of Free-standing GaN Template Grown by Hydride Vapor Phase Epitaxy", Solid State Electronics, Vol. **44**, pp. 2225 (2000).

2. Yun and H. Morkoç, D. L. Rode, F. Tsen, Ç. Kurdak, S. S. Park, and K. Y. Lee, "Analysis of electron transport in a high-mobility free-standing GaN substrate grown by hydride vapor-phase epitaxy" Spring 2001 MRS meeting April 2001, San Francisco.

3. D. Huang, F. Yun, P. Visconti, M. A. Reshchikov, D. Wang, H. Morkoç, D. L. Rode, L. A. Farina, Ç. Kurdak, K. T. Tsen, S. S. Park and K. Y. Lee, "Hall mobility and carrier concentration in GaN free-standing templates grown by hydride vapor phase epitaxy with high quality" Solid State Electronics, Vol. 45(5), pp.711-715 (June 2001).

4. H. Morkoç, "Comprehensive Characterization of Hydride VPE Grown GaN Layers and Templates" Material Science and Engineering Reports (MSE-R), Vol. 259, R33/5-6, pp. 1-73, 2001

Abstracts of selected publications made possible by the instrument:

Electrical, Structural, and Optical Characterization of Free-standing GaN Template Grown by Hydride Vapor Phase Epitaxy

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Department of Electrical Engineering and Physics Department

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Abstract

Electrical, structural, and optical properties of a free standing 200 um thick n-type GaN template grown by hydride vapor phase epitaxy (HVPE) have been investigated. Hall mobilities of 1502 $cm^2/V{\cdot}s$ and $9240 cm^2/V{\cdot}s$ have been obtained at room temperature and 50 K, respectively. Quantitative analysis of acceptor concentration, donor concentration and donor activation energy has been conducted through simultaneous fitting of the temperature dependent Hall mobility and carrier concentration data which led to a -donor concentration of 8.4×10^{15} cm^{-3} and an acceptor concentration of 5.0×10^{14} cm^{-3},The resultant donor activation energy is 26 meV. The analysis indicates that the electron mobility at high temperatures is significantly influenced by crystal defects. But the dominant scattering mechanism at low temperatures is by ionized impurities. The extended defect concentrations on Ga and N-faces were about 5×10^5 cm^{-2} for the former and about 1×10^7 cm^{-2} for the latter, as revealed by a chemical etch. The full width at half maximum (FWHM) of the symmetric (0002) X-ray diffraction peak was 69 and 160 arcsec for the Ga and N-faces, respectively. That for the asymmetric (10-14) peak was 103 and 140 arcsec for Ga-face N-faces, respectively. The donor bound exciton linewidth as measured on the Ga and N-face (after a chemical etch to remove the damage) is about 1 meV each at 10K. Instead of the commonly observed yellow band, this sample displayed a green band, which is centered at about 2.44eV.

Hall mobility and carrier concentration in free-standing high quality GaN templates grown by hydride vapor phase epitaxy

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Abstract

Measured and calculated (without any adjustable material parameter) electron Hall mobility and carrier concentration in the range of 26.5 to 273 K are reported for a high-mobility free-standing bulk GaN grown by hydride vapor phase epitaxy. The peak electron mobility of 7386 $cm^2/V.s$ at 48K and a value of 1425 $cm^2/V.s$ at 273K were measured. An iterative solution of the Boltzmann equation was applied to calculate the mobility using the materials parameters either measured on the sample under study or recent values that are just becoming available with only the acceptor concentration being variable. Using only one donor and one conducting layer system, the donor and acceptor concentrations of 1.76×10^{16} and 2.4×10^{15} cm^{-3}, respectively, satisfy simultaneously the charge neutrality and electron mobility at all temperatures within the framework of the iterative method and measurements. The donor activation energy was determined to be 25.2 meV and is consistent with the value of about 30 meV for the hydrogenic ground state in a dilute semiconductor. The high electron mobility, low background impurity concentration, low compensation ratio, and negligible dislocation scattering demonstrate the high quality of the material studied.

Comprehensive Characterization of Hydride VPE Grown GaN Layers and Templates

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Abstract

GaN community has recently recognized that it is imperative that the extended, and point defects in GaN and related materials, and the mechanisms for their formation are understood. This is a first and an important step, which must be followed by defect reduction before full implementation of this material and its allied binaries/ternaries in devices. This review is based on a recent concerted effort to establish benchmarks as far as defects are concerned, and identify the basic issues involved. Samples were analyzed for extended defects by TEM and chemical etches, for polarity by Electric Force Microscopy and convergent beam electron diffraction (CBED), for point defects by DLTS, for optical quality and deep defects by PL, for vacancies by positron annihilation, for donor and acceptor like states within the gap by ODMR and EPR, and for carrier transport targeted for defects and impurities by variable temperature and magnetic field dependent Hall measurements.

Hydride VPE samples grown at Lincoln Laboratories with 1.5 μm, 5.5 μm and 55 μm thicknesses were investigated for defects by TEM, and their polarity was found to be Ga-polarity, as expected, by CBDE combined with simulations. The density of misfit dislocations at the substrate-epi interface was determined to be on the order of 10^{13} cm^{-2} based on high-resolution electron microscopy images. The threading dislocation density decreased gradually with distance from the interface, reaching a value of about 10^8 cm^{-2} at the surface of a 55 μm film. A 200 μm thick laser separated and free-standing HVPE grown GaN template grown at Samsung was also characterized similarly. The free surface and substrate sides were confirmed to be Ga- and N-polarity, respectively. The density of dislocations near the N-face was determined to be, in order, $3 \pm 1 \times 10^7$ and $4 \pm 1 \times 10^7$ by cross-sectional TEM and plan-view TEM, respectively. Identical observations on the Ga-face revealed the defect concentration to be less than 1×10^7 cm^{-2} by plan-view TEM and 5×10^5 cm^{-2} by cross-sectional TEM.

Defects in a 10 μm thick GaN layer grown by HVPE at Lincoln Laboratory have been investigated by photo electrochemical (PEC) etching, and by wet etching in hot H_3PO_4 acid and molten KOH. Threading vertical wires (i.e. whiskers) and hexagonal-shaped etch pits are formed on the etched sample surfaces by PEC and wet etching, respectively. Using atomic force microscopy, one finds the density of "whisker-like" features to be 2×10^9 cm^{-2}, the same value found for the etch-pit density on samples etched with both H_3PO_4 and molten KOH. Values agree well with TEM results.

A free standing GaN template has been characterized for its structural and optical properties using X-ray diffraction, defect delineation etch followed by imaging with atomic force microscopy (AFM). The Ga-face and the N-face of the c-plane GaN exhibited a wide variation in terms of the defect density. The defect concentrations on Ga and N-faces were about 5×10^5 cm^{-2} for the former and about 1×10^7 cm^{-2} for the latter, again in good agreement with TEM results mentioned above.

High resolution X-ray rocking curves (omega scans) were measured. The [002] symmetric and [104] asymmetric peaks in 10 μm thick HVPE films had FWHM values between 5.8 and 7.9, and 3.9 and 5.2, respectively. The Samsung template investigated had wide diffraction peaks (20.6 and 24 arcmin for [002] and [104] diffractions, respectively) on the Ga-face, similar for the N-face, when a 2 mm slit size was used. When the slit size was reduced to 0.02 mm, the Ga and N-face [002] peaks reduced to 69 and 160 arcseconds. A bowing radius of 1.2 m was calculated to account for increased broadening with wider slits.

In the HVPE layer studied, SIMS investigations indicate that both O and Si concentrations drop rapidly away from the surface into the sample- mainly due in part to the artifact of the technique and in part due to condensates on the surface of the sample, down to about 10^{17} cm^{-3} for Si and high 10^{16} cm^{-3} for O. The Ga-face profile in the Samsung template indicated levels below mid 10^{16} cm^{-3} for all three of the impurities. The picture is different for the N-side, however, as it was juxtaposed to the substrate during growth and was mechanically polished after laser separation. The impurity concentration on this face, depending on the species, is some 1-3 orders of magnitude higher than the case for the Ga-face.

Transport properties as a function of the layer thickness, ranging from about 1 to 68 μm, while all the other parameters being the same, as they evolve from the sapphire-GaN interface and up were determined in epitaxial layers. A strong dependence on distance from the interface was observed with the averaged mobility figures increasing from 190 cm^2 $V^{-1}s^{-1}$ in the 5 μm film to 740 cm^2 $V^{-1}s^{-1}$ in the 68 μm film. The preliminary differential Hall measurements indicate that the mobility at the surface of the thick layer is about 1200 cm^2 $V^{-1}s^{-1}$. Electron mobilities in free-standing template were 1425 cm^2/Vs at T=273 K and 7385 cm^2/V·s at 48.2 K. By using the most recent unscreened acoustic deformation potential and allowing only the acceptor concentration to vary (2.4 x 10^{15} cm^{-3} for the best fit), one obtains an excellent fit to the measured mobility in the temperature range of 30 – 273 K by using an iterative BTE method. In addition, an excellent fit for the temperature dependent electron concentration was also obtained utilizing the acceptor concentration determined from the fit to the Hall data, and the charge balance equation. This led to a donor concentration of 1.6x10^{16} cm^{-3}, and activation energy of 26 meV, the latter being the highest reported in the literature for GaN.

In the freestanding template, the Γ_5 and Γ_6 free excitons were identified from emission measurements by utilizing polarization geometries where the E field is perpendicular to the c axis, favoring the Γ_5 exciton, and E field parallel to the c-axis (incident beam from the edge of the wafer) favoring the Γ_6 exciton. Focusing on the defect region of the PL spectrum, the N-face of the sample exhibited the usual yellow line. However, the Ga-face exhibited a broad band encompassing both yellow and green bands. The yellow luminescence in the free-standing template is weak and can be easily saturated. In contrast, the green luminescence is dominant and is attributed to the isolated defect involving gallium vacancy, whereas the yellow luminescence is related to the same defect bound to dislocation or surface bound structural defect.

Deep centers have been characterized by DLTS in HVPE-grown GaN epilayers of different thickness and dislocation densities, and templates. The main deep centers, such as A_1, B, and D, show higher concentrations in thinner samples, which suggests a correlation to the high dislocation densities. Based on the anti-correlation between A_1 and B, which is observed in thin HVPE-GaN layers, the defect B was tentatively attributed to N_{Ga}. Centers A_1 and E_1 found in thin HVPE-GaN are very similar to centers A_2 and E induced by electron-irradiation, indicating their point-defect nature. Centers A, C, and D are not affected by 1-MeV electron-irradiation, thus ruling out the possibility of these centers being identical to any EI-induced centers; however, their nature remains unknown. As the layer thickness decreases, an increase of deep centers, both in species and concentrations, was clearly observed, which is believed to be closely associated with the significant increase of threading dislocations as revealed by TEM. Based on a comparison with EI-induced centers and an observation of anti-correlation, A_1 is tentatively assigned to N_I, and B to N_{Ga}. The template exhibited a new trap B', with parameters E_T=0.53 eV and σ_T=1.5 x 10^{-15} cm^2 on the Ga-face, in addition to the four traps commonly observed in various epitaxial GaN layers. For the N-face, an N-vacancy related trap E_1, with E_T=0.18 eV and σ_T=4 x 10^{-17} cm^2, was observed. On the other hand, the Ga-face sample contained trap C, with E_T=0.35 eV and σ_T=1.6 x 10^{-15} cm^2. This trap may be related to surface damage caused by the RIE process employed.

Electron beam and optical depth-profiling of thick (5.5 - 68 μm) n-type HVPE GaN samples have been carried out using electron beam induced current (EBIC) and micro-photoluminescence (PL) to determine the minority carrier diffusion length, *L,* and minority carrier lifetime. The minority carrier diffusion length increased linearly from 0.25 μm, at a distance of about 5 μm from the GaN/sapphire interface, to 0.63 μm at the GaN surface for a 36-μm-thick sample. The increase in *L* was accompanied by a corresponding increase in PL band-to-band radiative transition intensity as a function of distance from the GaN/sapphire interface. These observations in PL intensity and minority carrier diffusion length have been attributed to a reduced carrier mobility and lifetime at the interface and to scattering at threading dislocations.

Positron annihilation experiments have been conducted in HVPE films with varying thicknesses from 1 to 68 μm. Mg doped samples and bulk GaN platelets have also been investigated and the behavior of positron annihilation in Mg-doped samples established. Unlike the Mg-doped samples, the positron lifetime in the HVPE samples increased with decreasing lattice temperature. This was interpreted as acceptors in these n-type samples being due to Ga-vacancies as opposed to relatively shallow acceptor impurities. The similarities in the behavior of these samples and those investigated previously where the III/V ratio was changed also lend support to the Ga-vacancy argument. Previous investigations established that as the III/V is lowered by increasing the ammonia flow during the growth, the Ga-vacancy concentration increased. Using Mg-doped samples as a standard, the vacancy concentration was determined to be about 10^{17} cm^{-3} near the surface for the layer with a thickness greater than 30 μm. Assuming that the growth parameters in the set of layers with varying thicknesses that were investigated are the same, the Ga-vacancy concentration increases to mid 10^{19} cm^{-3} near the interface. Since the interfacial region is n-type and highly conductive, this region must also contain even larger concentrations of O and or N-vacancies with lead to n-type material. SIMS results already indicate mid 10^{19} cm^{-3} levels of O being present in this region. This has been attributed to O out-diffusion from sapphire as previously reported.

FTIR, ODMR and EPR measurements have been performed in GaN layers and templates. In FTIR measurements, two absorption bands corresponding to binding energies of 30.9 (Si) and 33.9 meV were found. Splitting of the binding energies with magnetic field is consistent with an effective mass of 0.22 m_o. Angular rotation studies were performed with the magnetic field oriented perpendicular and parallel to the c-axis to provide symmetry information. The ODMR on the 2.2 eV peak in a 5-10 μm thick GaN layer, the notorious yellow emission, showed signatures of shallow donor (effective mass like) and deep defect centers with g-values of 1.95 and 1.99, respectively. The 3.27 eV peak with resolved LO phonon replicas, which is the blue peak observed in many GaN films grown by a variety of methods, is attributed to transitions involving shallow acceptors with $g_{\|} \sim 2.1$ and $g_{\perp} \sim 2.0$. ODMR on the 2.4 eV "green" PL band in the free-standing template also revealed evidence for shallow donors with a g-value of 1.95 and other deeper centers. The larger linewidth of the shallow donor signal from the template, relative to that found for the epitaxial layers, is indicative of a lower concentration of this center, which leads to an increased hyperfine interaction. EPR studies confirmed the notable difference between the epilayers and the template, particularly the larger linewidths in the template due to the lower concentration of shallow donors. Specifically, the free-standing sample has about $6x10^{15}$ cm^{-3} uncompensated donors while the epilayers have a concentration about a factor of four higher.

Calculations indicate that incorporation of Si has a negligible effect on the lattice constant, but O and Mg can lead to an observable expansion of the lattice. Since values of the GaN lattice constant have often been based on bulk crystals that are now known to contain large concentrations of oxygen, the "true" GaN lattice constant is actually smaller than what has been measured for such crystals. Boron is an unintentional impurity that can be introduced during MBE growth. There has been speculation about whether B might act as an acceptor in GaN; this would require it to be incorporated on the nitrogen site. Computations indicate that incorporating B on the N site is energetically unfavorable. Even if it did incorporate there, it would act as a *deep*, rather than a shallow acceptor. Formation energies of H in AlN and GaN have also been calculated. The behavior of H in AlN is very similar to GaN: H^+ dominates in *p*-type, H^- in *n*-type. Surprisingly, H in InN behaves exclusively as a donor, i.e., it is *not* amphoteric as in GaN and AlN, but actually contributes to the *n*-type conductivity of the material.

Scanning thermal microscopy (SThM) has been applied to measure the local thermal conductivity of epitaxial GaN as it is affected to a large extent by phonon scattering, and a closer to the true value of this parameter can be obtained by a local measurement in areas of lower defect concentration such as those found in the wing regions of lateral epitaxially grown GaN. The method relies on a thermo-resistive tip forming one quadrant of a Winston bridge. The bridge is balanced with the tip heated followed by bringing the tip in contact with the sample under test which cools down due to thermal dissipation. However, the feedback circuit attempts to keep the thermo-resistance and thus the tip temperature the same. The square of the feedback voltage necessary for this is proportional to the thermal conductive. Accurate values can be obtained with calibration using known substrates such as GaSb, GaAs, InP, Si and Al metal. Using SThM, thermal conductivity, κ, values in the 2.0 – 2.1 W/cm-K in the wing regions of lateral epitaxially grown GaN, 1.70 – 1.75 W/cm-K in HVPE grown GaN, and 3.0 – 3.3 W/cm-K for free-standing AlN have been measured.

Analysis of Electron Transport in a High Mobility Freestanding GaN Substrate Grown by Hydride Vapor Phase Epitaxy

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ABSTRACT

Semiconductor nitrides have received a great deal of attention due to the demonstration of light emitters, light detectors, and high power amplifiers. Defects present, due in large part to a large lattice mismatch with the substrates used, prevent the full potential of this material system from being attained. Among all the substrate options explored so far, freestanding GaN templates appear ideal for homoepitaxial growth of GaN films. To this end, hydride vapor-phase epitaxial (HVPE) grown GaN templates with a thickness of more than 200 μm were thermally lifted off from the sapphire substrate and mechanically polished. Transport properties were investigated by variable temperature Hall measurements on the Ga-face, both as prepared and with the N-face etched further, in a temperature range of 26.5 to 300 K. For as prepared GaN, Hall mobilities of 1100 cm^2/V-s and 6800 cm^2/V-s were obtained at room temperature and ~50 K, respectively. A simultaneous fitting of mobility and carrier concentration was used to quantize the contribution of different scattering mechanisms. When the N-face was etched by about 30 μm, Hall mobilities improved to 1425 cm^2/V-s and 7385 cm^2/V-s at near room temperature. It was not room temperature. If I recall it was around 273 K. Please correct and 48.2 K, respectively. A numerical solution of the Boltzmann transport equation (BTE) that deals with the inelastic nature of electron scattering by polar optical mode was employed to determine the acceptor concentration. Raman spectroscopy was employed to obtain LO and TO phonon energies, which were then used in the above mentioned calculations. The best fittings of the mobility and carrier concentration data yield an acceptor concentration of $4.9x10^{15}$ cm^{-3} and a donor concentration of $2.1x10^{16}$ cm^{-3} for the as-prepared GaN. The acceptor concentration decreased to $2.4x10^{15}$ cm^{-3} after etching of the N-face. The donor activation energy is derived to be 25.2 meV. Our analysis demonstrated high quality of the freestanding GaN substrate with the highest reported electron mobility for the wurtzite GaN.

Quote for the acquisition of the Lake Shore model 7504

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Dr. Hadis Morkoc
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Sincerely,

Andrew Ian

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Life member: Sigma Xi, Phi Kappa Phi
Listed in Who's Who in the Midwest, American Men and Women in Science, Who's Who in America, Who's Who in Engineering, and International Men of Achievement.

PUBLICATIONS

Some 1050 publications, 37 book chapters, 42 review and popular articles, a two volume book on MODFETs and a book on Nitride Semiconductors and Devices. According to Institute of Scientific Information and since 1982, the research papers of Dr. Morkoç have been cited some 15, 000 times. Moreover, in a field encompassing, condensed matter physics, electronic materials, metallurgy, ceramics, polymers, and materials chemistry, and in the five year period 1990 - 1995 and for all publications world-wide: Dr. Morkoç was listed as 18 th and 4th in the total number of citations and the Citation Impact (number of citations per paper), respectively, see Science Watch, Vol. 6, No. 9, October 1995, and the Journal Science, October 20, 1995. According to the same organization, Morkoç ranked 19th among 517,111 physicists in terms of citations and citation impact between 1981 and 1997. There ahead of him were groups of physicists who shared the same last and first names. He is listed in two fields for having been highly cited, Engineering and Physics. He is only one in nine who are listed in more than one category.

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C. Recent Collaborators:

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E. Graduate advisor: Prof. L. F. Eastman, Cornell University

Synergistic Activities: The PI has established an undergraduate course in advanced concepts in semiconductors. In conjunction with that course, he trained 9 undergraduate courses on aspects of GaN ranging from growth, lithography, fabrication to analysis. He established the first ever GaN meeting iin the world which has spiraled into major meetings in the world, was instrumental in establishing other domestic and international meetings in GaN and related materials and devices for the dissemination of information. He wrote reports on the status and prospects on wide bandgap semiconductors, which were distributed very widely, and played a critical role in the popularization GaN. He wrote, and continues to do so, critical review papers, book chapters and a book on the topic. He also presented many seminars at numerous institutions, including many business concerns, across the globe to spread the message. He is currently editing a three volume book for Academic Press which brings together scientists from the physical, chemical and biological sciences to treat the topics that are likely to dominate the scientific and technological discourse. Last but not least, he collaborated with some 20 groups across the globe with varying backgrounds to advance the engineering and science of GaN.

Facilities available in the Virginia Commonwealth University Microelectronics RESEARCH LABORATORY (Inclusive of the Hall apparatus)

The micro and nano-electronics research and education is performed in the Virginia Microelectronics Center (VMC), a 27,000 square foot four-story building. The first floor of the VMERC is devoted to silicon technology and undergraduate education. The necessary equipment is being installed as provided by Motorola, Inc. The sponsored research programs are conducted on the third floor of the VMREC which has approximately 2500 square feet of class 1000 space. Even though the laboratory receives new tools continually, already, an MBE system designed for depositing nitride semiconductors has been installed and calibrated. The SVT Reactive MBE system is also equipped with a RF nitrogen source for maximum flexibility. In addition, the workhorse, perhaps the most well known MBE system in the world that the group of Prof. Morkoç has used since 1979, is producing device quality layers. This Riber 1000 MBE system has been converted to reactive MBE system. On the deposition side again, a custom MOCVD system designed for semiconductor nitrides has installed, and optimization runs are in progress. This custom MOCVD system has a gas manifold and deposition reactor which were manufactured by EMCORE Corporation and SVT Associates, respectively. The system gives the group the added flexibility and advantage for nitride research. It has tremendous latitude in terms of gas delivery and eliminates much of the interdependence among the parameters that often hampers conventional MOCVD systems. The group also was fortunate to have received a third MBE system as a gift from Bell Laboratories, Lucent Technologies. On the fabrication side, the research laboratory is equipped with photo and electron beam lithography systems and metallization and etching facilities. The LEO 440 microscope has a 2 nm resolution in the imaging mode and is layered with a Nabity pattern generation system. The research oriented RF dry etching system that was designed in the plasma group at Wright Patterson Air Force Research Laboratory. This system is designed for convenience and low damage and easily configurable for plasma diagnosis for an easy correlation of plasma parameters to etching characteristics.

Through and NSF MRI program, we have added a Philips X'pert MRD high resolution (10 arcsec which can be upgraded to 5) X-ray diffraction system in 1999. X-ray diffraction (XRD) is a versatile analytical technique used in our research to analyze structural properties of crystalline materials. At VCU the system will be used for high resolution applications – such as rocking curves of heteroepitaxial layers; diffraction space maps of thick hetero-epitaxial structures and partially relaxed structures; reflectivity measurements of layer thickness, interface/sample quality and density, and structural properties of nano-structures. The X'Pert - MPD system utilizes specially developed PREFIX (pre-aligned, fast interchangeable) optical modules which enable you to switch from application to application by simply swapping the optical module. Dedicated analytical instrument performance is ensured due to the wear-free reference surfaces on the PREFIX modules. The MRD cradle provides the versatility of an open Eulerian cradle, an x-y stage and z translation to accommodate applications needing utmost accuracy.

Another tool, KLA Tencor Alpha Stepper 500 surface prolifometer, is capable of mapping th e surface topology. This is a very versatile system for precise measurement of very thin step heights on wafers and small samples. Flexible software allows analysis of up to 39 surface parameters with simultaneous display. Moreover, we added a Digital Instruments Nanoscope III multimode AFM with STM capability which is pivotal in characterization layer growth including structural defects and charge states.

Extensive optical characterization facilities, which allow PL, absorption and reflectance measurements in semiconductor nitrides and other samples, also exist. The recently acquired Ti-Sapphire laser with Second Harmonic Generation (SDH) and Third Harmonic Generation (TDH) allows tunable wavelengths in the ranges of 700-100nm and 235-500 nm with picosecond temporal capabilities. In addition, He-Cd, N and Ar lasers are also available. The detection scheme is based on photon counting with excellent signal to noise ratio. The laboratory also has several cryostats. A diamond anvil cell with its associated optics, optical sources, a fast CCD detector, and 1.25 m spectrometer is in the process of being commissioned.

Recently, we added a Lake Shore Model 7504 Hall Effect Measurement System with automatic data acquisition in the temperature range of 10-300 K and magnetic fields up to nearly 1 T. This instrument is used to determine carrier concentrations and mobilities in semiconductors, and allows the determination of scattering processes taking place. A Keitley 4200 parameter analyzer, which is PC based, with below fA and above 1A current measurement capability, and coupled with a Karl Suss PM 8 shielded probe station provides an accurate and rapid evaluation of I-V characteristics. In addition, a temperature dependent I-V and C-V measurement capability is available with metrics software and Keithley electronic switch box for versatility in the choice of instrument connected to the device under test.

The deposition and fabrication laboratories enjoy conveniently delivered utilities such as gaseous and liquid nitrogen, process vacuum, compressed dry air, process cooling water, DI water, scrubbed and regular exhausts, and much more. The airflow system for class 1000 is designed to diffuse the air in a way to be extremely quiet. This combined with all the roughing pumps and compressors being located in service bays lend to a very comfortable and environmentally friendly laboratory space in which to work. Moreover, the group has electrical and optical characterization laboratories giving the researcher full access to a full range of equipment to carry out research without leaving the laboratory. The group has a long term working relationship with many specialists across the country and abroad for research requiring expertise and training not available on site.

For more details, pictures, and layout of the laboratories, please visit http://

www.engineering.vcu.edu/fac/morkoc

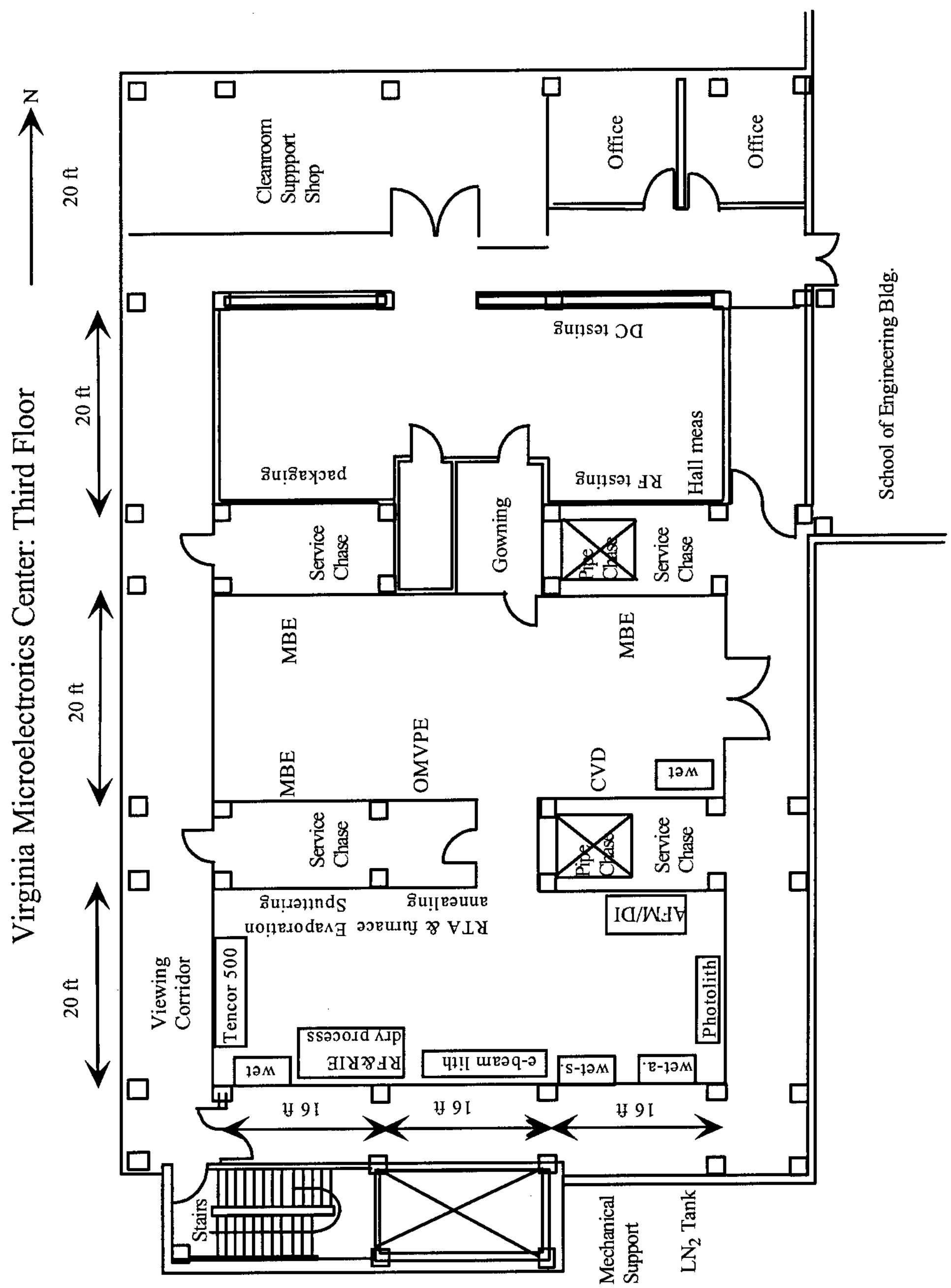

Fig. 1. Layout of the research present equipment and clean room in the Virginia Microelectronics Center. Layout of the research present equipment and clean room in the Virginia Microelectronics Center.